

TIRARI FORMATION AND CONTAINED FAUNAS, PLIOCENE OF THE LAKE EYRE BASIN, SOUTH AUSTRALIA.

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ABSTRACT

First recognized at Lake Palankarina, south-eastern Lake Eyre Basin, South Australia, the Tirari Formation has subsequently been traced northward to outcrops along the lower Warburton River. Unfossiliferous, red gypsiferous mudstone with interbedded cross-laminated gypsum sand is the most characteristic lithology. A basal stream-channel fill at Lake Palankarina, the Mampuwordu Member, contains the Palankarina Fauna, and a widespread nested sequence of channel fills at the top, the Pompapillina Member, produces the Toolapinna and Kanunka faunas. These faunas are dominated by extinct species and contain diprotodontid and macropodid genera not found in Pleistocene or Recent assemblages. They differ from older Tertiary faunas in that their taxa are more closely related to living or Pleistocene clades. The Kanunka and Toolapinna assemblages contain *Euryzygoma* Longman, *Prionotemnus* Stirton, *Kurrabi*, *Protomodon devisi* Bartholomai, and conilurine rodents in common with Pliocene faunas elsewhere in Australia. The presence of conilurine rodents suggests a maximum age of 4.5 Ma for the upper part of the Tirari Formation. Magnetostratigraphic studies indicate that the Tirari Formation is largely reversed in magnetic polarity, but contains normal intervals at and near the base at Lake Kanunka and the lower Warburton. Faunal evidence constrains correlation of the upper part of the Tirari Formation with the youngest reversed normal interval in the Gilbert Chron (3.9 - 3.4 Ma).

KEYWORDS: Lake Eyre Basin, Tirari Formation, lithostratigraphy, magnetostratigraphy, biostratigraphy, Palankarina fauna, Toolapinna fauna, Kanunka fauna.

INTRODUCTION

In their pioneer study of the Cainozoic deposits of the Lake Eyre Basin in South Australia, Stirton, Tedford and Miller (1961) coined the name Tirari Formation for the "flat lying brick red argillaceous sandstones and arenaceous claystones" that overlie the Etadunna Formation regionally, and the Mampuwordu Sand locally at Lake Palankarina, the type locality for all these lithostratigraphic units. The Tirari Formation rests with angular unconformity on the gently folded Etadunna Formation at Lake Palankarina. Its relationship with the fossiliferous channel-filling sands and clays of the Mampuwordu Sand were considered to be disconformable but there is no evidence of erosion or reworking of the Mampuwordu Sand into the overlying Tirari red

mudstones. We now believe that these units record aspects of a single basin-filling event, the Tirari Formation. The local channel fills at the base become the Mampuwordu Member of the Tirari Formation (Fig. 1).

In 1961, the Tirari Formation had been traced to outcrops on the lower Cooper (Katipiri Waterhole) and northward into the central Tirari Desert at Lakes Kanunka, Pitikanta and Ngapakaldi, where the stratigraphy showed the same general sequence as at the type locality. At that time, all supra-Tirari channel-filling sands and clays were grouped as the Katipiri Sand, although it was clearly recognized that the fossil assemblage from these rocks at Lake Kanunka was markedly different from the other local faunas from the Katipiri Sand. The Kanunka Fauna was considered early Pliocene in age

by Stirton, Tedford and Woodburne (1968: Fig. 2).

In 1980 and 1983 the authors initiated field work to resolve questions about the latest Cainozoic (post-Etadunna) stratigraphy and paleontology east of Lake Eyre. All previously known outcrops were reinvestigated, new fossil collections were made, and outcrops along the lowest reaches of the Cooper and Warburton were examined, as well as those on the eastern shore of Madigan Gulf, Lake Eyre North. These field studies were guided and complemented by aerial reconnaissance, study of airphotos and LANDSAT imagery. The results of our work on the Pleistocene deposits and faunas were reported in 1986 (Tedford *et al.* 1986) and the present contribution summarizes the Pliocene deposits and their faunas. Some of our biochronological conclusions were incorporated into Woodburne *et al.* (1985), and a preliminary synthesis of the Pliocene and Pleistocene history of the Lake Eyre Basin was given by Tedford *et al.* (1986).

We have retained the serial identification of marsupial cheek-teeth as used by Stirton (1955), rather than that of Archer (1978). Abbreviations used: AM, Australian Museum, Sydney; AMNH, American Museum Natural History, New York;

SIAM, field catalogue of Smithsonian Institution, Washington - American Museum of Natural History collections; SAM, South Australian Museum, Adelaide; UCMP, University of California. Museum of Palontology, Berkeley.

LITHOSTRATIGRAPHY

At its type locality, the exposures along the bluffs marginal to the western shore of Lake Palankarinna, the main body of the Tirari Formation shows a rather consistent stratigraphy and thickness. The unit can be characterized as red-brown (10R4/5-6 Munsell) claystones, clayey sands and sandy clays, thin-bedded to laminated where structure is visible. Although these rocks are locally cemented with gypsum, they do not contain abundant authigenic gypsum. The basal silty, very-fine to fine sands contain scattered coarser grains and intraformational clay clasts, but lack clasts from the adjacent silcreted older Cainozoic and Mesozoic rocks. A widely traceable bed of white, very-fine to medium quartz sand, 0.25 m thick, containing red-brown clay pellets and lenses, occurs about 1 m above the base of the unit throughout the Lake Palankarinna exposures.

<i>Stirton, Tedford, Miller: 1961</i>		<i>Tedford and Wells: 1990 & this paper</i>		
ROCKS	FAUNAS	ROCKS	FAUNAS	
<i>Katipiri Sand</i>	<i>Malkuni</i>	<i>Katipiri Fm.</i>	<i>Malkuni</i>	
	<i>Kanunka</i>	<i>Kutjitara Fm.</i>	<i>Lower Cooper</i>	
<i>Tirari Fm.</i>		<i>Tirari Fm.</i>	<i>Pompapillina Mbr.</i>	<i>Kanunka Toolapinna</i>
			<i>Main Body</i>	
			<i>Mampuwordu Mbr.</i>	<i>Palankarinna</i>
<i>Mampuwordu Sand</i>	<i>Palankarinna</i>			
<i>Etadunna Fm.</i>	<i>Ngapakaldi</i>	<i>Etadunna Fm.</i>	<i>Ngapakaldi S.I.</i>	

Fig. 1. Comparison of lithostratigraphic and biochronologic nomenclature, Pliocene and Pleistocene rocks and faunas, eastern Lake Eyre Basin, South Australia, over the past thirty years.

The upper quarter of the Tirari Formation contains shallow festoon cross-bedded, fine to medium quartz sands that pass upward into red-brown mudstones. Small celestite nodules occur in the mudstones beneath this sandy interval. Intense gypsum cementation characterizes the upper 2 m, indurating a widespread surface on which the Quaternary dunefield rests. This gycrete represents a major morpho-stratigraphic

unit (Wopfner and Twidale 1967) in the Lake Eyre Basin.

The Mampuwodu Member has been recognized only in the northern part of the Lake Palankarinna escarpment where it is represented by the fill of perhaps a single stream channel excavated in places at least 5 m into the Etadunna Formation. The basal sands in the channel contain pebbles of the Etadunna Formation (green

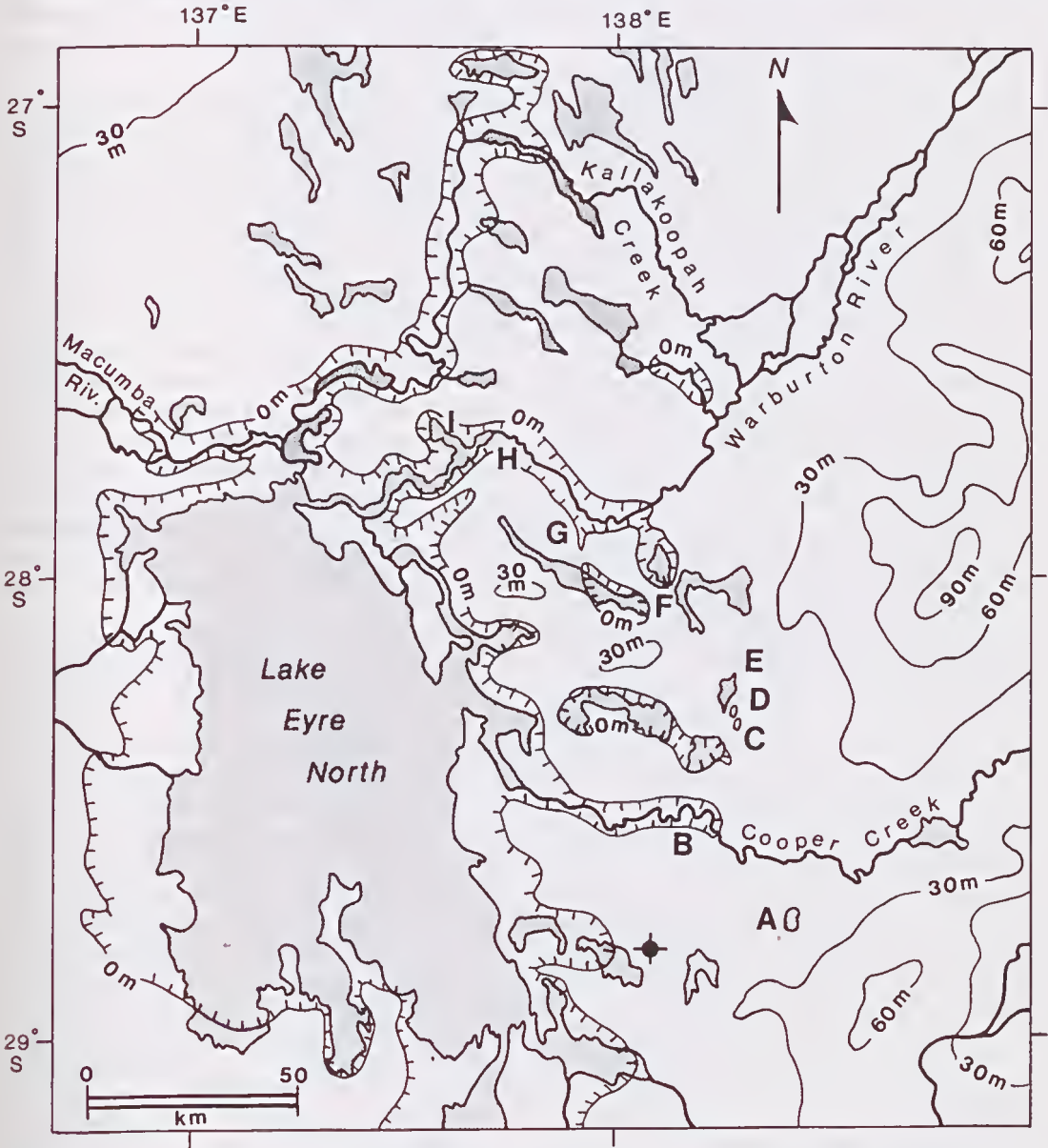


Fig. 2. Topographic map of the region east and northeast of Lake Eyre North. Contour interval 30 meters modified from Twidale and Wopfner (1990: fig. 2). Sites discussed in this paper: A, Lake Palankarinna; B, Katipiri Waterhole; C, Lake Kanunka; D, Lake Pitikanta; E, Lake Ngapakaldi; F, Lake Kittakittaooloo; G, Toolapinna Waterhole; H, Keekalanna Soakage; I, Lake Pompapillina. Symbol for exploratory well is Peachawarinna 2 and 2A.

mudstone and dolomite) and redeposited polished silicified pebbles ultimately derived from the Paleogene Eyre Formation. The Mampuwordu channel-fill contains cross-laminated, fine, white quartz sands, green to black clay lenses and clayballs, and locally abundant vertebrate remains ranging from small fragments up to a 1 m wide diprotodontid pelvis. Observations of foreset bedding in the fossil excavations were few, but were of consistent orientation indicating northward transport along the trend of the exposed channel segments.

Outcrops of the Tirari Formation along lower Cooper Creek begin just west of Lake Tarlakupa and extend 6 km westward to Katipiri Waterhole and perhaps 5 km further west to "Red Bluff." These outcrops form the northern edge of the ancestral Cooper meander belt, which is incised into the Tirari and overlying Kutjara Formations. Red-brown mudstones compose the lower part of the local Tirari sequence overlain by a plexus of interbedded, northward trending, stream channels filled with cross-bedded sands and interbedded mudstones. The upper part of these sands are heavily impregnated with gypsum, forming a gypcreted geomorphic surface beneath the dunes.

South of the Cooper, the Tirari Formation is buried beneath Quaternary fluvial deposits. This is indicated in the Peachawarinna 2 and 2A cores drilled by the Bureau of Mineral Resources about 34 km south of Katipiri Waterhole. In these drill holes, nearly 12 m of reddish sands and interbedded clays with a gypsum indurated cap lie on the Etadunna Formation. The gypcrete caprock is overlain by 13.5 m of Quaternary fluvial and aeolian deposits.

North of the Cooper, the Tirari Formation crops out in the escarpments along the western sides of Lakes Kanunka, Pitikanta and Ngapakaldi. At the first two sites the stratigraphy is identical. Lower red-brown and green mottled mudstones, up to 4 m thick, are disconformably overlain by fossiliferous, cross-bedded, white and ferruginous, medium grained sands with lenses of red-brown claystone, green and red clay balls and scattered pebbles of carbonate rock, silicified and kaolinized sediments derived from the Etadunna Formation and the older rocks of the basin margin. The sands were deposited in a deeply dissected landscape cut into the red mudstones (and into the Etadunna Formation at Lake Kanunka) so that the thickness of the channel-fill varies from a meter or so to nearly 6

m. Gypsum concretions are common along the basal contact of the channel-fill, especially where it overlies the Etadunna Formation. Intensive gypsum cementation indurates the top of the section, holding up the sand-draped edge of a plateau that extends from Lakes Kanunka to Ngapakaldi.

A similar stratigraphy occurs farther north in the Tirari Desert along the western side of Lake Kittakittaooloo, where channel-sands overlie red brown mudstones that rest on silicified and ferruginized dark claystones referred to the Etadunna Formation.

Erosion during development of the Warburton meander belt in Quaternary time seems to have cut a broad swath into the Etadunna Formation, removing the Tirari Formation upstream from Toolapinna Waterhole. The long escarpment that borders the western side of the Warburton River from Toolapinna Waterhole nearly to Lake Pompapillina shows 15 m of Tirari Formation, the thickest in the region. In places, the escarpment has been undercut, giving rise to large slump blocks that have been rotated along curved slip-surfaces. Along this 30 km reach of the Warburton River, the Tirari Formation has a consistent stratigraphy that permits lithological correlation between outcrops. Contact with the Etadunna Formation can be seen at Toolapinna waterhole, and all traceable beds decline to the north-west at an angle greater than the present gradient of the river floor.

As in the south, the Tirari Formation along the lower Warburton can be divided into two units separated by a disconformity. The lower unit, or main body of the Tirari Formation, is red-brown gypsiferous mudstone that comprises about two-thirds the 15 metre maximum observed thickness. Sedimentary structures are difficult to observe, but those visible in the sandier units imply thin to laminated beds. A basal fine quartz sand contains limestone pebbles and reworked celestite nodules derived from the underlying Etadunna Formation. These sands fill fractures in the top of the Etadunna Formation. Above the basal metre, quartz is subordinate to authigenic gypsum seed-crystals as the coarsest clastic component in the red-brown claystone. At 4.5 m above the base, a widely traceable, bench-forming unit of horizontal to cross-laminated, medium gypsum sand occurs. Planar foreset laminae and ripple lamination indicate north to north-west transport of elastic gypsum. A more indurated ripple-laminated greenish gypsum sand occurs 8-9.5 m

above the base. This widely traceable unit bears rolled charophytes, disarticulated fish-bones, rare mammal bones and scattered limestone pebbles and granules. Above this distinctive bed, authigenic gypsum is rare and quartz dominates the coarser sand fraction. The upper third of the section is composed of interestered stream channels that cut as much as 3 m through the upper laminated gypsum sand into the underlying red mudstones. Celestite nodules frequently occur beneath this contact. These fluvialite deposits include festoon cross-laminated, medium to coarse quartz sand with red-brown claystone lenses that fine upward to climbing-ripple laminated fine sands and interbedded clays, and finally massive red-brown mudstone in the most completely preserved cycles. Occasional fossil mammal remains occur in the basal part of these channel deposits.

The consistent occurrence of such quartzose fluvialite deposits at the top of the Tirari Formation, from its type section to the Warburton River, encourages us to name this member to facilitate discussion of an important event in the history of the Lake Eyre Basin. We have chosen the name Pompapillina Member from the lake nearest the most northerly outcrop of the unit along the Warburton, but designate the type section at Toolapinna Waterhole.

We have not been able to recognize the Tirari Formation downstream from Lake Pompapillina, nor among the outcrops along the Kallakoopah to the north. Shallow drilling in the southern Simpson Desert north of the Kallakoopah, but south of the South Australia-Northern Territory border, has revealed nearly 100 m of red-brown fluvialite sediments overlying the Etadunna Formation that have been attributed to the Tirari

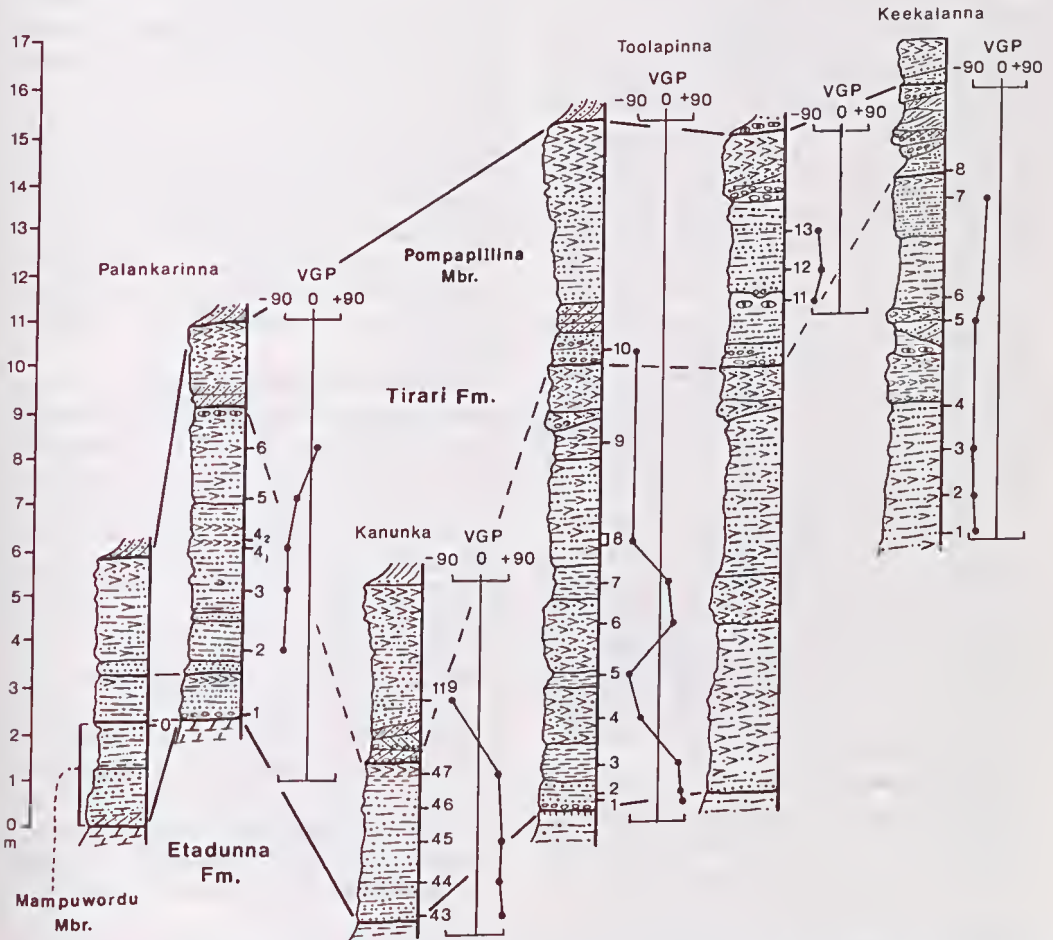


Fig. 3. Correlated stratigraphic columns of the Tirari Formation showing lithostratigraphy with conventional lithological symbols ("v" denoting gypsum) and lithostratigraphic correlations. Magnetostatigraphy depicted by values for the Virtual Geomagnetic Pole (VGP).

Formation (Wasson 1983). This region also contains the thickest (subsurface) development of the Etadunna Formation, suggesting a stable depocenter from Miocene into medial Pleistocene time, based on the cited thicknesses and the presence there of Kutjitarra Formation prior stream deposits (Tedford and Wells 1990) as well. The persistent northward indications of transport provided by Tirari sedimentary structures and textural trends points to a depocenter north of Lake Eyre.

MAGNETOSTRATIGRAPHY

Thirty-three paleomagnetic sites were established in four local sections of the Tirari Formation. Eighteen of these sites gave site mean paleopositions which were statistically significant using minimum conventional criteria. We interpreted the remaining site mean paleopositions to have reversed or indeterminate polarities, based upon individual sample demagnetization behavior. Thus we concluded the Tirari Formation stratotype (Lake Palankarinna) and local section at Keckalanna Soak to be uniformly of reverse polarity; the Toolapinna Waterhole reference section to be mixed polarity, but largely reversed; and the local section at Lake Kanunka to be of mixed but largely normal polarity (Fig. 3).

The behavior of samples during both alternating field and thermal step-wise demagnetization indicated the presence of a viscous component of Natural Remanent Magnetization (NRM) readily removed at low treatment levels (10 mT, 100° C). With increasing demagnetization, the remaining remanence did not appear to be consistently resolvable into components of distinct coercivity ranges or orientations. More complete step-wise removal of NRM was achieved with thermal demagnetization, and this was the preferred magnetic cleaning procedure. Nonetheless, magnetic cleaning was not sufficient to identify the polarity of all sites with respect to the simple geomagnetic dipole model.

Methods. *Collecting and Laboratory Procedure.* Stratigraphic site sampling interval was to average 1 m, but was adjusted to allow for outcrop exposure and lithologic type. Finer-grained lithologies were preferred: i.e. mudstones, silty mudstones, and finer-grained siltstones, although some medium to fine sandstones were also sampled. A minimum of

three samples was collected at each site, except at the Lake Kanunka local section where a large number of samples were taken. Lateral spacing of samples ranged from 1m to 8m, but was usually in the 3-4.6m range. Samples were extracted by hand tools from consolidated sediments beneath the surface weathered zone. As the stratotype section at Lake Palankarinna is more severely weathered, it required deeper trenching. Bearing and dip data for each sample face was measured by Brunton Compass corrected for local declination.

In the laboratory, cube specimens (2.5cm) were cut from the oriented hand samples with a band saw, and cleaned to size with non-magnetic abrasive paper. Duplicate (contiguous) cubes were cut from a single sample wherever possible (labelled -i, -ii, etc.). Many of the samples from the Palankarinna section cracked upon drying and it was not possible to cut them with the saw. Crumbly samples were consolidated by placing them face up in tailored aluminum foil boats and flooding them with liquid paraffin. The resulting block was then trimmed to size. Some of the more deeply cracked samples retained so much wax that thermal demagnetization treatment was not possible. Thermal demagnetisation was not possible for Keckalanna Site 4 (partially) and Palankarinna Sites 1 (partially), 2 (partially), 3, 4 (partially), 5 and 6. Their mean palaeopositions were calculated from treatment in alternating fields only.

Specimen determinations were run on an ScT 3-axis Cryogenic Magnetometer. A custom plastic sample holder was used, which introduced an average moment intensity error of approximately $14 \times 10^{-9} \text{ A m}^{-1}$ over the course of the laboratory determinations. Alternating-field (af) demagnetizations was carried out on a Schoensted demagnetizer (non-tumbling), while thermal demagnetization was carried out in a Schoensted thermal demagnetizer.

Magnetic cleaning of all samples was achieved by step-wise demagnetization with the minimum of two, but usually six, treatment levels. For af treatment, vector and point diagrams were constructed at 10 mT increments up to 90 mT. For the thermal treatment, diagrams were plotted for 100°C increments up to 600°C; specimens were held at each temperature level for 40-45 minutes.

Demagnetization curves. Magnetic cleaning, or partial demagnetization by either alternating field or thermal procedures, serves to "strip"

portions of the initial sample NRM, leaving a smaller net magnetic moment after each step. Thus, decreasing net portions of the initial sample NRM are measured, i.e. those portions which are resistant to the randomizing effects of the elevated fields or temperatures, or in other words, those portions whose coercivity exceeds the randomizing energy of the peak treatment level at each successive step. The demagnetization behavior is analysed to identify discrete coercivities, or coercivity ranges (spectra), of

the components of the total NRM. NRM orientation and stability (coercivity) provide clues to the magnetic history of the rock. However, it is not always easy to relate the resolvable components of NRM to specific events in the postdepositional history of the rock. Using the conventions for the vector-end-point diagram (developed by Zijderfeld, 1967) used in Fig. 4, the magnetic moment vector of each determination is represented by two points which share a common abscissa value and whose disposition

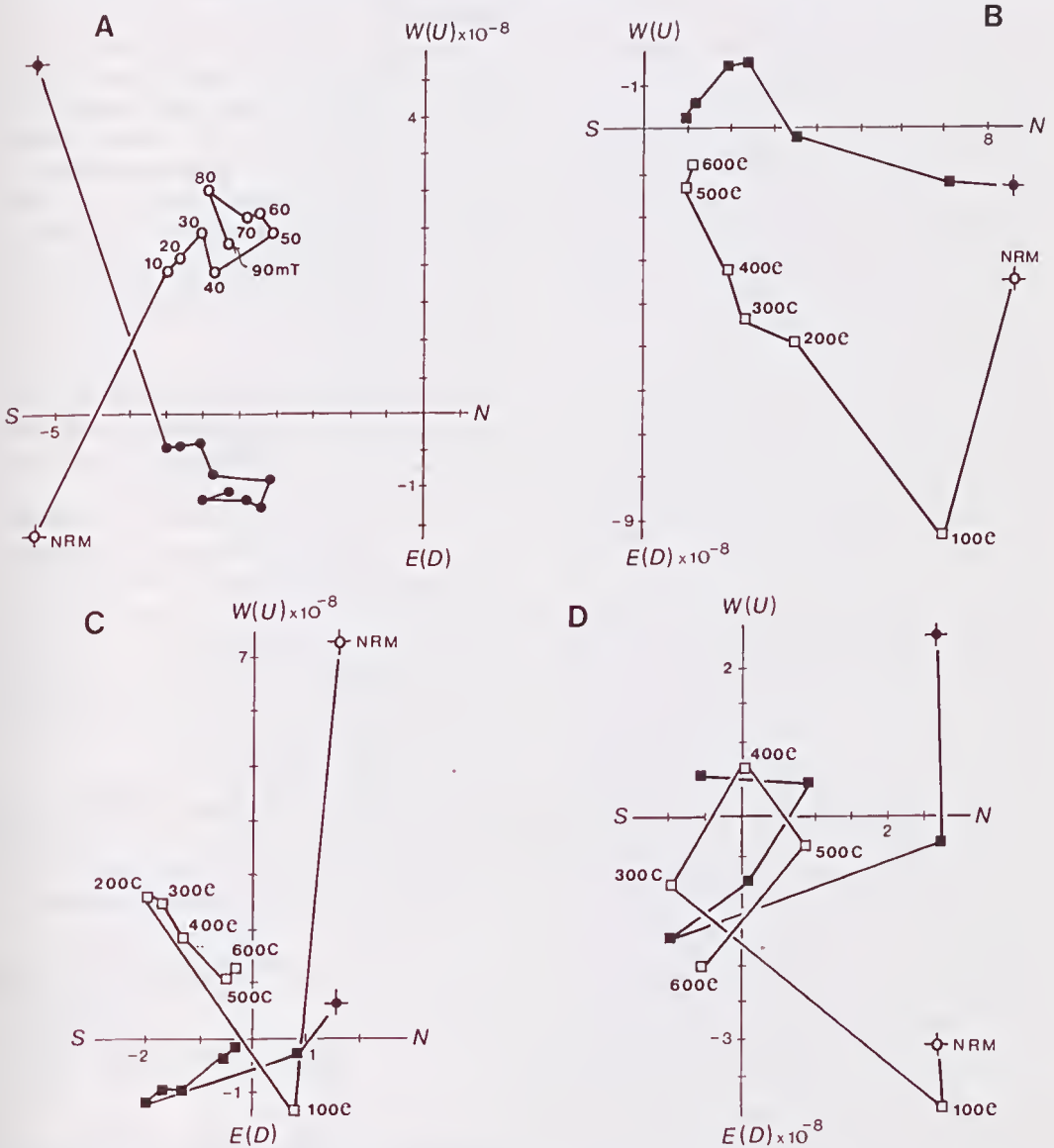


Fig. 4. Vector end-point (Zijderfeld) diagrams for four representative Tirari samples. A; sample PK-2c, B; sample KN-45c, C; sample KE-6a, D; sample KE-7b. Conventions: squares-thermal, circles-af, treatment; open symbols-inclination, closed symbols-declination, component of NRM vector. Intensities normalized to 10 cc sample volume, Am^{-1} .

together reflect the three-dimensional orientation of the measured NRM. The distance of the points from the origin reflects the length of the vector, and is a measure of the intensity of magnetization remaining. The removal of a given component of NRM after a certain demagnetization level may be followed by a distinct shift in orientation and/or intensity of the remnant signal. This results in either a more linear demagnetization curve, or distinct progression towards the origin. Overlapping coercivity spectra in multicomponent NRM signals will produce smoother curves if the component orientations are varied, or if all the components of NRM are parallel, a steady linear decay of the curves towards the origin. Alternatively, a wide scattering of points and no distinct progression of curves towards the origin may indicate unstable or unreliable magnetization, whose components cannot be clearly differentiated or explained, at least for the purposes of polarity stratigraphy. It may also be due to spurious signals introduced during the laboratory procedure.

Results. Figure 4 shows vector end-point diagrams for four specimens subject to step-wise demagnetization. These are representative of the behavior of Tirari samples. A variety of demagnetization curves was exhibited over the entire population of treated samples. These curves were segregated into several general categories, as explained below and with reference to Figure 4.

At lowest treatment levels, both af and thermal, all samples show the removal of a component of NRM with a substantial reorientation of net remanence. Usually this component comprises about 10% to 30% of the intensity of original NRM. Presumably this component consists of Viscous Remanent Magnetization (VRM) in part, and accounts for the variety of orientations observed. It is due to the procedures for handling and storage of the trimmed specimens. A portion of this lowest coercivity NRM may also be overprint from recent (normal) geomagnetic field acquired *in situ* and is a common source of VRM. No detailed study of this low-coercivity component was made to resolve these moieties. After removal of viscous component(s) at mid-range treatment levels (i.e., up to 400°C, 50 mT), most samples displayed a consistent range of orientations and more steady decay of intensity of net remanence. This mid-range component of NRM was used to derive site mean paleopositions. Alternating field cleaning to higher levels (up to

90 mT) did not prove to be effective in removing the remaining remanence. Higher thermal treatment (500°C to 600°C) often led to relative increases in intensity of magnetization, and substantial reorientation. However, the low strength of the remaining remanence, combined with the often widely divergent directions at these high temperature levels, led us to suspect laboratory contamination. These determinations were rejected in deriving polarity assessments.

Sample PK-2c (Fig. 4A) illustrates the incomplete effectiveness of af treatment. Stable orientation of net remanence is indicated at mid and high field levels, but there is incomplete progression to end-point (i.e., complete demagnetization or randomization of the NRM signal). This sample is interpreted to be of reversed polarity.

Sample KN-45e (Fig. 4B) shows satisfactory progression toward end-point with thermal cleaning, with more or less stable behavior of orientation over a broad range of coercivities. The increase of intensity with initial treatment may be due to removal of VRM acquired in the handling and storage of the specimen. The lack of intensity drop at the 600°C may reflect introduction of a spurious signal, although this is not substantial with this specimen. Samples with similar curves are considered to be stable samples, in this case of normal polarity.

Sample KE-6a (Fig. 4C) also shows satisfactory progression towards the end-point with thermal cleaning. In this case, it is possible that two moieties of low-coercivity remanence have been resolved by the determination at 100°C. The higher-temperature part is closely anti-parallel to the remaining net NRM. Again, a spurious signal appeared at the highest temperature. This sample is concluded to be reversed.

Sample KE-7b (Fig. 4D), in contrast KE-6a, shows no pattern of orientation of NRM at mid and high treatment levels, and no progression to end-point. It is considered to be unstable, and consequently polarity cannot be determined.

Table 1. Mean Intensity values for Tirari Formation samples. Intensity units: $\times 10^6$ A m⁻¹, normalized for 10cc sample volume.

Transect	NRM (M ₀)	Cleaned (M)	Ratio (M/M ₀)	No. of Samples
Toolapinna	0.891	0.305	0.342	39
Keekalanna	0.703	0.179	0.254	24
Palankarina	2.012	0.728	0.362	24
Kanunka	1.719	0.620	0.361	41
Tirari Fm	1.331	0.462	0.347	128

Other Magnetic Characteristics. Table 1 lists means of sample intensities of magnetization, by section, before (M_0) and after (M) magnetic cleaning. Values for cleaned samples are from the ones used in determining the site means. The values for NRM intensity indicate that Tirari sediments were comparatively weakly magnetized. The mean intensity ratio for the entire sample population was $M/M_0=0.347$, indicating that the site mean paleopositions were based on the highest coercivity third of original remanence. This portion of the original NRM was presumably well above the coercivity spectrum of the viscous component(s). As discussed above, more deeply eroding the NRM with greater demagnetization may have lead to problems of weak or spurious signals.

Six samples were uniaxially magnetized to 5.0T, which introduced an artificial remanence known as the Isothermal Remanent Magnetization, or IRM. At such high applied fields, nearly all of the magnetic mineral domains were forced into alignment with the applied field (H): that is,

the sample is said to be saturated. These samples were then demagnetized stepwise to remove the IRM signal, by placing them in progressively higher fields oriented antiparallel to the saturating field ($-H$). The strength of the demagnetizing backfield required to totally remove all the IRM signal is the coercivity of isothermal remanent magnetization, or $-H_{cr}$.

The resulting IRM curves (Fig. 5) show that full saturation was not achieved for any of these samples at the peak field of 5.0T (Fig. 5, curves from origin at left). The back-curves (Fig. 5, right, plotted to the $-H$ axis) show a range of coercivities of IRM ($-H_{cr}$). Samples TP-7c and KE-2d both show very similar low intensities of IRM saturation and high values of $-H_{cr}$ (83 mT, 760 mT, respectively), which is consistent with hematite-borne remanence. These samples are from nearly equivalent levels of the Toolapinna and Keekalanna sections (qv. lithologic correlation Fig. 3). Sample PK-5c, in contrast, shows high saturation IRM intensity and low $-H_{cr}$ value (28 mT), a pattern more consistent for magnet-

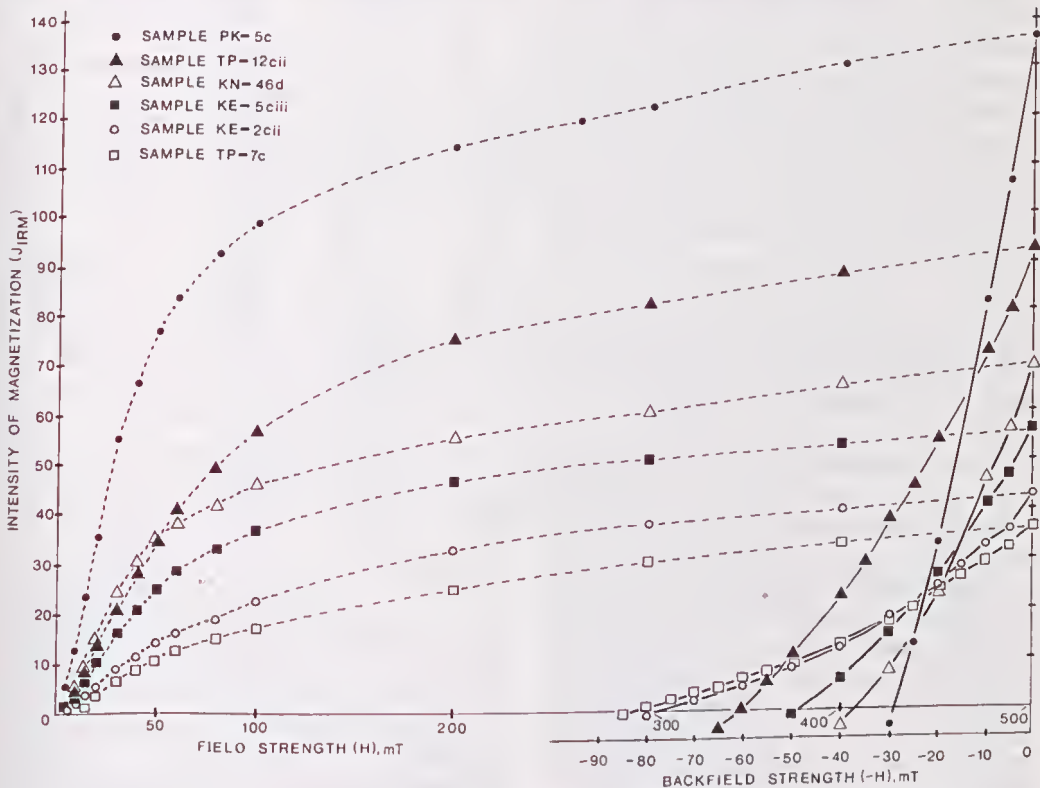


Fig. 5. IRM curves for six representative Tirari lithologies sampled. Sample TP-7c: red/green mudstone with minor silt; previously treated to 600°C. TP-12cii: medium fine sandstone with evaporites. KE-2cii: very fine-grained red/green mudstone. KE-5ciii: medium-fine, well cemented, brown sandstone with gypsum. PK-5c: red mudstone/fine sandstone; previously treated to 60 mT. KN-46d: fine, well sorted brown sandstone, previously treated to 60 mT. Units: intensity of IRM, $\times 10^{-1}$; saturating and back field strengths, mT.

ite-borne remanence. The intermediate nature of the other samples, such as Sample TP-12c, indicate that the magnetic mineralogy of these sediments is more likely a combination of the two magnetic mineral groups, hematite and magnetite.

Mean Paleopositions for Sites. Site mean paleopositions were calculated from averaged sample paleopositions, before and after magnetic cleaning. The resulting paleopositions were selected from those treatment levels which appeared to reflect the stable spectrum of determinations (i.e. clustered orientations accompanied by directionally-steady or low-intensity declines of nett remanence). In the vector-end-point diagram convention, those points group along straight-line or tightly flexured portions of the curves.

For our samples, the most effective cleaning temperature was 300°C (usually) or 400°C. In some cases where samples could not be cleaned thermally, an alternating field strength of 50 mT was most effective.

Figure 6A, B show site mean paleopositions for all sites, before and after cleaning. It is apparent that overprint component(s) of NRM before cleaning obscure any pattern of polarity stratigraphy. Sediments susceptible to overprinting gave reversed orientations before cleaning. The magnetic cleaning did, however, resolve nearly antiparallel polarities, with the emergence of two populations of site means (Fig. 6B), but left considerable scatter among the reversed sites.

Site mean results and statistics are listed in Table 2. Statistical significance is defined only by the minimum values for R (Fisher's Vector Sum) as conventionally applied (e.g., McElhinney, 1973). For each of the samples for a given site, the R value calculated for the mean must exceed the established minimum threshold R value to ensure a 95% probability that the mean has not been calculated from a population of randomly-oriented vectors. Three samples per site is the minimum required to achieve statistically meaningful R values. By these criteria, the site means of 18 of the 33 sites are statistically significant. Inference on polarity of other sites can be tentatively advanced, based on the following informal categorization of sites:

Class I - statistically significant site mean paleoposition, normal or reversed;

Class II - not statistically significant, but with sample paleopositions evenly scattered about the calculated mean, and/or R near threshold

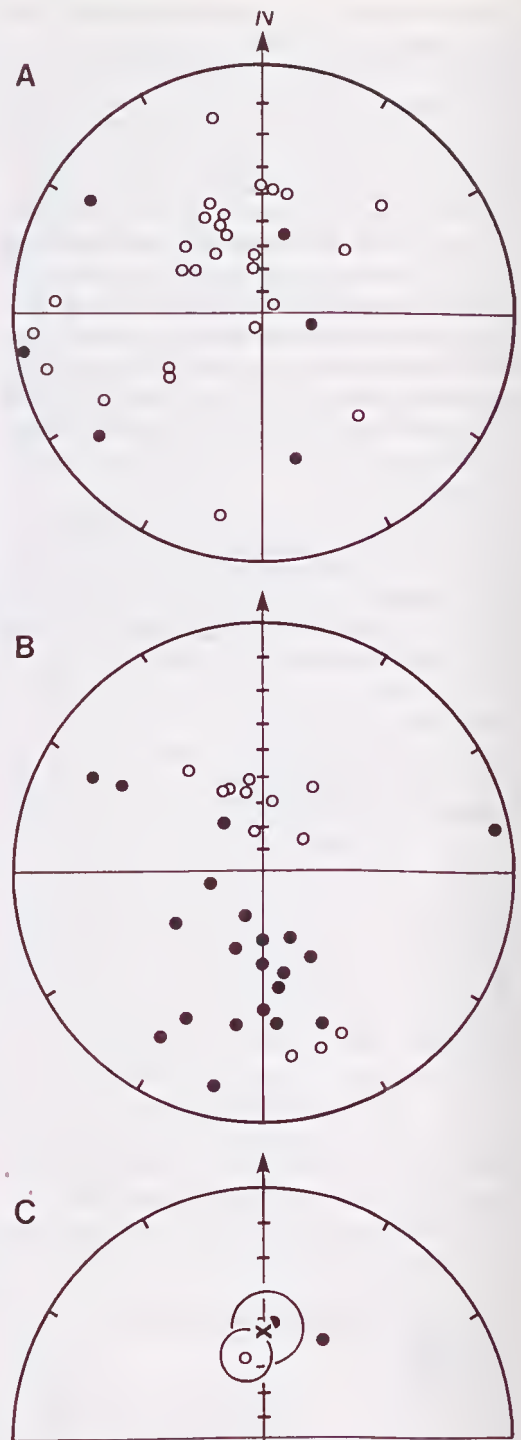


Fig. 6. Mean paleoposition of all sites, stereographic projection. A, before, B, after magnetic cleaning; C, reversal test for all statistically significant sites (reversed sites mean translated to northern hemisphere; circles of 95% confidence plotted). Open symbols=negative, closed symbols=positive, inclinations. "X"-present day geomagnetic dipole position for 28°S latitude.

Table 2. Tirari Formation Palaeomagnetic Site Means & Statistics; Columns: N= number of samples; k= precision parameter; Cof C=circle of 95% confidence; R= Fisher's Vector Sum; Pal'pos'n=Site mean paleoposition; P'lat. = Site paleolatitude; VGP=virtual geomagnetic pole. "Class", Pol.=Polarity - see text.

Site	N	k	CofC	R	Pal'pos'n		P'lat.	VGP Position		"Class"	Pol.
Toolapinna Waterhole											
1	3	42.1	12.5	2.9525	351.3	-50.2	31 S	72.2 E	81.8 N	I	N
2	3	6.6	31.5	2.6987	347.0	-55.6	36.1 S	88.1 E	76.2 N	I	N
3	3	8.2	28.2	2.7552	334.2	-51.8	32.4 S	65.8 E	67.3 N	I	N
4	3	11.9	23.4	2.8319	160.8	-17.0	8.7 S	167.6 E	49.0 S	IV	?R
5	3	2.0	57.2	1.9878	179.4	50.8	31.5 N	145.9 E	86.3 S	II	?R
6	3	44.0	12.2	2.9545	323.1	-38.0	21.3 S	50.7 E	56.0 N	I	N
7	3	6.6	31.5	2.6972	78.9	3.9	2.0 N	220.9 E	8.9 N	IV	?R
8	3	4.1	39.9	2.5100	189.0	27.3	14.5 N	104.1 E	74.2 S	III	?R
9	3	0.9	85.2	0.7630	50.6	-66.6	49.1 S	184.8 E	46.1 N	V	I
10	3	6.8	31.0	2.7077	174.7	28.9	15.4 N	160.5 E	76.6 S	I	R
11	3	4.2	39.4	2.5260	180.2	59.4	40.2 N	137.2 E	77.7 S	II	?R
12	3	5.6	34.2	2.6419	211.6	14.0	7.1 N	76.7 E	53.6 S	I	R
13	3	1.8	60.2	1.8910	193.3	8.2	4.1 N	106.5 E	62.8 S	III	?R
Keekalanna Soak											
1	3	13.0	22.4	2.8457	199.7	67.0	49.7 N	108.6 E	63.4 S	I	R
2	3	3.3	44.5	2.3955	156.4	59.1	39.9 N	189.6 E	67.0 S	II	?R
3	3	155.0	6.5	2.9871	170.6	45.5	27.0 N	224.9 E	81.6 S	I	R
4	3	1.0	80.8	0.9144	170.4	-16.5	8.4 S	153.5 E	52.7 S	V	I
5	3	12.5	22.9	2.8406	172.6	42.1	24.3 N	202.4 E	82.5 S	I	R
6	3	526.3	3.5	2.9962	150.8	48.2	29.2 N	217.4 E	64.3 S	I	R
7	3	2.7	49.2	2.2658	153.3	-19.2	9.9 S	176.0 E	44.4 S	IV	?R
8	3	0.9	85.2	0.8311	298.6	14.7	7.5 N	68.8 E	21.1 N	V	I
Lake Palankarinna											
1	7	1.4	44.7	2.5828	257.4	65.1	47.1 N	89.1 E	28.9 S	V	I
2	6	3.3	31.5	4.4745	200.0	55.1	35.6 N	75.6 E	71.8 S	I	R
3	3	2.3	53.3	2.1251	207.6	24.0	12.6 N	75.0 E	59.6 S	III	?R
4	3	9.4	26.4	2.7871	159.2	22.2	11.5 N	191.0 E	64.0 S	I	R
5	3	6.7	31.2	2.7024	239.0	45.4	26.9 N	61.3 E	38.3 S	I	R
6	2	3.4	53.7	1.7023	321.7	62.2	43.5 N	111.3 E	9.7 N	III	?R
Lake Kanunka											
43	3	5.7	33.9	2.6480	337.1	-51.7	32.3 S	65.3 E	69.9 N	I	N
44	9	5.3	20.3	7.4788	348.2	-71.7	56.5 S	125.0 E	60.6 N	I	N
45	9	2.6	28.9	5.9306	6.3	-59.4	40.2 S	160.3 E	77.1 N	I	N
46	8	1.2	45.2	1.9933	300.6	23.4	12.2 N	75.0 E	19.7 N	V	I
47	5	5.7	26.2	4.2968	31.6	-48.8	29.7 S	217.7 E	62.4 N	I	N
119	7	73.2	6.2	6.9180	179.2	33.1	18.1 N	142.5 E	79.6 S	I	R
Tirari/Formation Means, statistically significant ("Class I") sites only											
	8	25.0	9.9	7.7204	348.6	-55.2	35.7 S	91.2 E	77.1 N		N
	10	10.5	13.7	9.1459	184.1	42.9	24.9 N	77.9 E	85.7 S		R

value; mean paleoposition oriented as expected for normal or reversed polarity;

Class III - not statistically significant, two of three or three of four samples, however, consistent, and the remaining sample(s) divergent; polarity assigned from non-divergent samples;

Class IV - statistically significant or not, with sample paleopositions apparently consistently oriented in anomalous directions (e.g., south-seeking declinations and negative inclinations), or "intermediate" directions, not fully normal or reversed polarities. These sites possibly reflect

tracking of intermediate geomagnetic field positions, but are considered more likely to be the result of unsuccessful magnetic cleaning;

Class V - not statistically significant, with wide scatter of sample positions, reflecting no interpretable pattern of orientation, or magnetically unstable samples; polarity indeterminate.

Following this classification, the polarity of sites in Table 2 are concluded to fall in one of four categories: statistically significant normal (N); statistically significant reversed (R); tentatively reversed (?R); or indeterminate (I). Indetermi-

nate (Class V) sites were excluded from further consideration. All normal sites were Class I, and their samples gave consistently normal orientations, indicating that discernible, high-coercivity (stable) reversed overprint is not a major component of NRM. In contrast, cleaned samples of sites in Classes II-IV did not give normal orientations, but rather consistently reversed, scattered reversed, or incompletely reversed directions. Polarity assessment of these latter sites indicates that they are probably reversed, although affected by incomplete magnetic cleaning or introduction of spurious signals in weakly magnetized samples.

Summary means for all normal and the reversed sites for the Tirari Formation as a whole are included at the end of Table 2, based only on statistically significant means (Class 1 sites), and plotted in Figure 6C.

Paleomagnetic Stratigraphy. Paleomagnetic stratigraphy is indicated in Figure 3, expressed as tracking of Virtual Geomagnetic Pole (VGP) latitude and in Figure 7, as inferred normal (solid symbol) and reversed intervals. Accepting the tentative use of all but Class V sites, the main

body of the Tirari Formation at the Toolapinna reference section indicates the presence of four magnetozones, with most of the upper part of the sampled section of reversed polarity. The Keekalanna section is uniformly reversed, which is consistent with its lithologic correlation with the upper part of the Toolapinna section. On this basis, the Keekalanna results help to confirm the uniformly reversed character of the upper Toolapinna section, although we do not have the coverage we would prefer in the sandy 7 to 9m zone of the Toolapinna reference section. The main body of the Tirari Formation at the Lake Palankarina type section is also uniformly reversed. In contrast, the main body of the Tirari Formation at the Kanunka section is uniformly normal. The Pompapillina Member is uniformly of reversed polarity at all localities where it has been determined.

An indication of the reliability of the 1 m sampling interval is provided by the combined results from the Toolapinna and Keekalanna sections. Vertical site density is closer to twice the normal in the 5 to 6 m (main body) and 11 to 13 m (Pompapillina Member) ranges. Were the

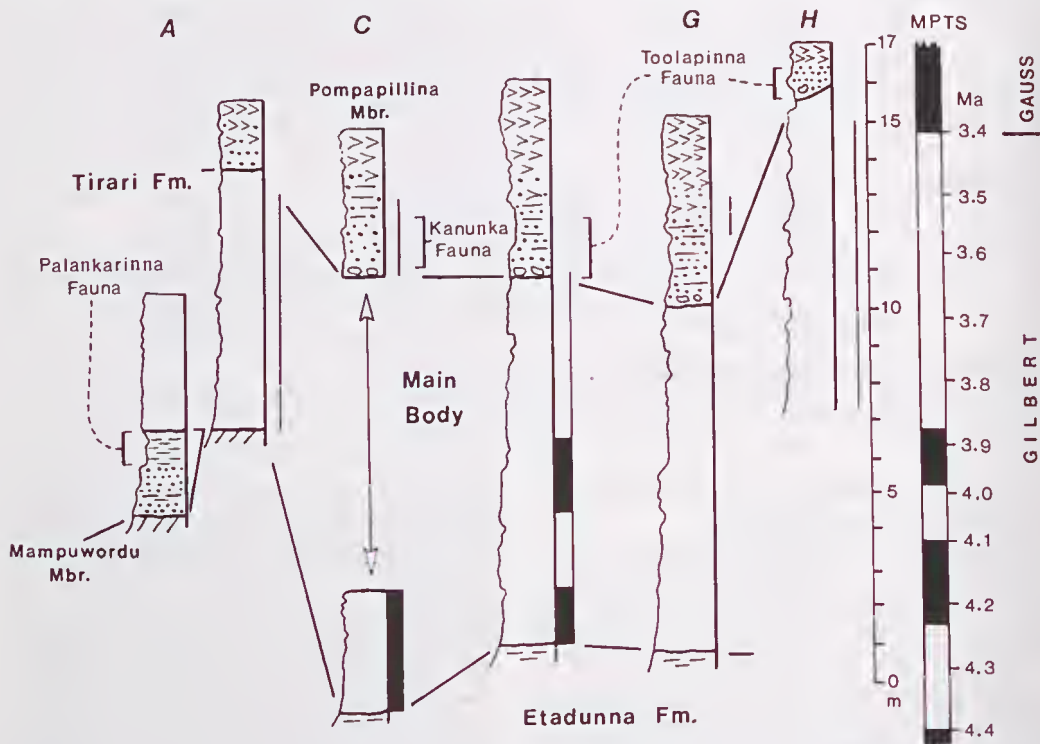


Fig. 7. Summary of litho-, magneto- and biostratigraphy depicted by a simplification of Fig. 2, adding stratigraphic position of fossil vertebrate assemblages discussed in the text. Magnetostratigraphy summarized to right of each lithological column (black indicates normal polarity), and favored correlation to the Magnetic Polarity timescale (MPS) indicated.

Tirari postulated to represent substantially more geologic time than we currently envisage, and our usual sampling interval were so broad as to detect only a fraction of polarity intervals actually recorded in the section, these two intervals might be expected to document more magnetic events. Such a pattern is not observed for either member of the Tirari formation, suggesting that our sampling interval is appropriate for the sedimentation rate(s) of these deposits, and therefore the amount of geologic time represented by the units.

The broad picture of this polarity stratigraphy is unchanged, albeit with considerably less resolution, with the exclusion of all sites which are not statistically significant. The primary magnetostratigraphic information indicated by inclusion of the additional sites in classes II-IV is the resolution of an additional reversed magnetozone in the lower part of the Toolapinna section (Sites 4 and 5), which implies greater time represented by the Tirari Formation in this reference section.

BIOSTRATIGRAPHY

When defined in 1961, the Tirari Formation was thought to be unfossiliferous, but as regional stratigraphic evidence began to build, it was recognized that the referred "Katipiri Sand" at Lake Kanunka should be referred to the Tirari Formation (Woodburne *et al.* 1985) as part of the plexus of stream channel-fills (now the Pompapillina Member) in the upper part of that unit at most other outcrops in the Tirari Desert. Although it could not be distinguished lithologically from Pleistocene channel-fills (Kujitara and Katipiri), it was everywhere involved in the episode of intensive groundwater gypsum cementation that typified the oldest gypcrete in the Lake Eyre Basin.

We have also incorporated the "Mampuwordu Sand" of Stirton, Tedford and Miller (1961) into the Tirari Formation as the basal member. These are local stream deposits filling shallow valleys at the base of the formation near the southern margin of the Lake Eyre Basin.

In the 1980s we discovered *in situ* fossil remains in the Tirari Formation along the lower Warburton River. Rare post-cranial elements of medium-sized macropodids were found in the upper part of the gypsiferous mudstones in the main body of the Tirari Formation and in the base of the uppermost gypsum sand beneath the

Pompapillina Member, but the majority of the remains were taken from the basal part of the Pompapillina Member at Toolapinna Waterhole, and from outcrops south of Camel Swamp Yard and east of Keekalanna Soakage. These local faunas from correlative stratigraphic positions have been united as the Toolapinna Fauna.

Palankarinna Fauna. The Palankarinna Fauna was obtained from the Mampuwordu Member at the base of the Tirari Formation. It was the first Tirari age fauna known and the only one completely described. The local fauna of the Woodard Quarry at Lake Palankarinna supplied the first sample, described by Stirton in 1955. Discovery of the Lawson-Daily Quarry in 1957, the Keane Quarry in 1962, and Mullet Locality in 1971 provided further local faunas, each different in composition or abundance. The Woodard Quarry yielded mostly *Prionotemmus* Stirton and the diprotodontine *Meniscolophus* Stirton, the Keane Quarry nearly exclusively *Zygomaturus* Mcleay without other vertebrates, the Mullet Locality, near the Keane Quarry, yielded *Zygomaturus* and *Prionotemmus* whereas the Lawson-Daily Quarry had both diprotodontid genera plus ratite birds and abundant *Prionotemmus*. The Palankarinna Fauna as a whole is very limited in taxonomic diversity although rich in individuals of the forms present. Only the *Zygomaturus* from the later excavations was described (Stirton 1967). The large sample of *Prionotemmus palankarinnicus* Stirton now available at the University of California Museum of Paleontology (UCMP) would allow fuller description of the morphology of this otherwise rare macropodine. The holotypes of these species reside in the South Australian Museum (SAM).

The Palankarinna Fauna includes the following.

Pisces. Lungfish dental plates and disarticulated remains of unidentified teleost fish were found at the Woodard and Lawson-Daily Quarries.

Reptilia. Chelonia: Unidentified turtle remains are recorded from the Woodard Quarry (Stirton 1955).

Crocodylidae: Crocodile teeth are well represented at all sites. A right maxilla (UCMP 113956) and isolated teeth represents a ziphodont crocodylian thought to be either a eusuchian or sebecosuchian (Hecht and Archer 1977). Teeth of *Crocodylus* Gmelin are also present.

Aves. Two ratites are present, an extinct emu *Dromaius ocybus* Miller, 1963b, represented by a tibiotarsus and a dromornithid recorded by a

fragment of a synsacrum (UCMP 60613) identified by Miller (1963b) as *Genyornis* sp. (see comments in Rich, 1979:56). No other bird remains are recorded.

Mammalia. Peramelidae: The holotype and only known specimen of the extinct bilby *Ischnodon australis* Stirton, 1955, was collected at the Woodard Quarry.

Diprotodontidae: Stirton (1955) initially described the diprotodontine *Meniscophylus mawsoni* Stirton from the Woodard Quarry. This taxon is also the most abundant diprotodont in the Lawson-Daily Quarry, but it is rare in the Keane Quarry where *Zygomaturus keanei* Stirton, 1967, is the dominant form. *Zygomaturus keani* occurs at all the sites. Stirton (1967) described, but did not name, a smaller *Zygomaturus* from the Lawson-Daily Quarry that he thought was significantly different from *Z. keanei*.

Macropodidae: In all of the Palankarinna sites with macropodids, *Prionotemnus palankarinnicus* Stirton, 1955, is dominant.

There is evidence for two other taxa. A medium-sized sthenurine, possibly *Simosthenurus* Tedford, is represented by a lower incisor with typical short and deep crown (UCMP 45420) and a lumbar vertebra (57086). A larger macropodine, possibly *Protomnodon* Owen, is represented by a tibia (UCMP 57195) and an ulna (60909) of comparable size. These fragments give evidence of a more diverse fauna, including some of the larger kangaroo genera that occur in other Pliocene and Pleistocene sites.

Kanunka Fauna. This collection was obtained from the lower part of the fill of a single stream channel that crops out along a salient and associated isolated hill ("SAM Hill") in the north-western part of the dissected escarpment bordering the Lake Kanunka saltpan. This channel trends to the north-west and cuts through the lower Tirari Formation and into the top of the Etadunna formation. It has the stratigraphic, lithologic and diagenetic features of the Pompapillina Member of the Tirari Formation as seen at other sites, the only difference being the Tirari red-brown mudstones are thinner here than elsewhere, presumably because Lake Kanunka is nearer the basin margin.

The Kanunka Fauna was obtained mostly from Stirton Quarry on the escarpment salient, but also from prospect pits around SAM Hill and from float on the Etadunna Formation beneath these outcrops. The fauna is taxonomically diverse, but nearly all the remains are fragmentary,

as typical of an energetic fluvial environment, the holotype ramus of *Troposodon kenti* being one of the more complete specimens. The major collection from these sites resides at the Museum of Paleontology, University of California, Berkeley, but a few specimens are contained in the American Museum of Natural History, New York, the Australian Museum and Zoology Department of the University of New South Wales, Sydney and the South Australian Museum Type specimens are housed in the South Australian Museum, Adelaide.

The Kanunka Fauna contains:

Pisces. Lungfish dental plates and isolated teleost remains of unidentified species are abundantly present. Some teleost vertebrae imply the presence of large fish.

Reptilia. Chelonia: Gaffney (1981) described and figured chelid shell fragments that are part of the Kanunka Fauna.

Squamata: Hecht (1975) recorded the presence of *Megalania* Owen in the Kanunka Fauna.

Crocodylia: Isolated crocodile remains are abundant at the Kanunka sites, and most pertain to *Crocodylus* sp.

Aves. In addition to remains referable to the living emu, *Dromaius novaehollandiae* (Latham), described by Patterson and Rich (1987), Rich *et al.* (1982) record a diverse assemblage of water birds. Pelicans are represented by remains of the living *Pelecanus conspicillatus* Temminck and the extinct *P. cadimurka* Rich and Van Tets, 1981, and the aningas by the extinct *Anlinga novaehollandiae* Miller, 1966. Rich *et al.* (1987) record three flamingos: one close to the living Greater Flamingo, *Phoenicopterus ruber* Linnaeus; an extinct form, *Xenorhynchopsis minor* (DeVis, 1905), similar in size to the living Lesser Flamingo, and a smaller extinct species *Ocyplanus proeses* (DeVis, 1905) with which Miller's (1963) *Phoeniconaias gracilis* can be equated. Other waterbirds include representatives of Ciconiidae, Ardeidae, Anatidae, and Gruidae (*Grus* sp.). The Rallidae, Otidae and passeriform birds are also represented. A giant eagle (*Aquila* Briss. sp.), larger than the living wedge-tail, is also present.

Mammalia, Marsupialia. Dasyuridae: At least two species are represented by fragmentary material. Two maxillary fragments (UCMP 56900), edentulous except for the last molar, are the size of the largest *Dasyurus* Geoffroy. A right ramus with canine, P₁₋₃ alveoli and well worn M₁₋₄ (UCMP 60800) is the size of *Dasyercus*

cristacauda (Kreffit), but retains a P_1 crowded against the outside of the canine.

Vombatidae: Wombats are represented by three isolated teeth from Lake Kanunka, but at nearby Lake Pitikanta a palate of a large wombat was collected from the Pompapillina Member. The latter specimen is under study by Eric Wilkinson. The Kanunka teeth indicate the presence of *Phascolonus* Owen and a small wombat comparable to living forms.

Diprotodontidae: In contrast to other Tirari Formation sites, the Lake Kanunka locality produced few identifiable diprotodontid remains. Despite statements to the contrary in Stirton, Tedford and Miller (1961), *Diprotodon* sp. is represented by three incisor teeth: the tip of a lower incisor (UCMP 60810), a left I^3 (in the University of N.S.W. collection) and a right I^2 (UCMP 56916) all of which are well worn and could represent a single individual. *Zygomaturus* sp. (not *Euowenia* fide Stirton, Tedford and Miller, 1961) is represented by an unerupted left M^4 (UCMP 56917) and the posterior part of a lower molar (probably M_3 , UCMP 56918). These teeth are similar in size to *Z. keanei* although perhaps a little higher-crowned. There are fragments of the teeth of other, smaller, diprotodontines, but none is complete enough to verify the occurrence of *Euryzygoma* or other forms.

Thylacoleonidae: *Thylacoleo* sp. is represented by an isolated M^1 .

Macropodoidea: This is the most abundantly represented group, but specimens complete enough for identification are rare among the many isolated and broken teeth and post-cranial remains.

Potoroidae: *Bettongia* Quoy and Gaimard is represented by a new species similar in size to *B. leseur* Quoy and Gaimard but with bicuspid M_4 talonid, narrower molars, narrower and more recumbent ascending ramus. A right ramus (UCMP 56902) and right maxillary (UCMP 56915) pertain to this taxon. A larger potoroid is indicated by an isolated left M_4 about twice the length of the same tooth of *Bettongia*.

Macropodinae: Smaller macropodine remains are more abundant than larger ones, and the group as a whole has a significant Kanunka representation.

One of the surprises in the Kanunka collection is a right maxillary fragment (AMNH field number SIAM 70) with the posterior alveolus for P^3 , the roots of M^1 , M^2 with labial face broken

away and M^3 with only the anterolabial part of the anterior eingulum preserved. The M^2 corresponds morphologically to that of *Dendrolagus* Muller and it is only about 10% larger than "cf. *Dendrolagus* sp. 2" from the Bow Fauna of northeastern New South Wales (Flannery and Archer 1984) and about twice the size of species of the living genus. A large dendrolagine, *Bohra paulae* Flannery and Szalay 1982, has been described from postcranial elements from the Wellington Caves, but no teeth referable to this taxon have been identified. The Kanunka and Bow fragments indicate that large tree kangaroos were also present in the Pliocene of Australia.

Two species of *Lagorchestes* Gould are present, the smaller is the most completely represented by a right ramus of an old individual with complete cheek tooth dentition (UCMP 60809) appears to be a new form about the size of *L. leporides* Gould. The larger form is represented by two jaw fragments (UCMP 56922 and unnumbered) that show $M_{1,2}$, M_3 erupting and dP_3 - M_1 respectively. This taxon is slightly larger than living *L. conspicillatus* Gould.

Two species of genus *Protemnodon* are present. The best represented is a small species closely similar in size and morphology to *P. devisi* Bartholomai, 1973a. A nearly complete left ramus (UCMP 56894) allows full comparison with topotypes. Fragmentary maxillae, teeth and metapodials of appropriate size can also be referred to this form. There is also a larger species indicated by an isolated M_4 (UCMP 56904) the size and crown height of *P. brehus* Owen.

The presence of *Prionotemmus* is suggested by fragmentary material, none of which show the diagnostic dP_3 . Among the most likely remains is a left ramal fragment with M_1 , M_2 erupting (UCMP 129197) which differs from topotypic *P. palankarimicus* in slightly greater tooth dimensions, height of crown and wider anterior eingulum, but is otherwise morphologically similar to the topotypic sample. An isolated M_4 is within the dimensions of *P. palankarimicus*.

Another left-ramal fragment with broken M_1 and erupted little worn M_2 (UCMP 56912) is the size of *Kurrabi mahoneyi* Flannery and Archer with which it agrees in morphology particularly in replacement of the posterior eingulum by a pit on M_2 .

A small wallaby is represented by several ramal and maxillary fragments. Although not demonstrably conspecific, they all agree best in

morphology and size with species of the pademelon *Thylogale* Gray, especially with *T. stigmatica* (Gould) which has relatively large upper and lower third premolars.

Larger macropodines are very rare in the Kanunka collections. Flannery and Archer (1982) report the occurrence of *Macropus* (*Macropus*) *pearsoni* (Bartholomai, 1973b) collected by the University of New South Wales from the type locality (AM F 64000). There is also a smaller *Macropus*, represented by a left ramus with lower incisor, P₃, dP₃, M_{1,2}, M₃ uncrupted (UCMP 60777) that closely matches *M. (M.) woodsi* Bartholomai, 1975, in size and morphology. The lower incisor in this specimen shows the long crown and extensive distribution of enamel onto the ventrolabial face that Dawson and Flannery (1985) held diagnostic of *Macropus* (*Macropus*) species. Isolated upper molars, designated paratypes of *Troposodon kenti* Campbell, by Campbell (1973), UCMP 56907 and 60825, are also referable to *M. (M.) woodsi*.

Sthenurinae: Relatively primitive sthenurines are present in the Kanunka fauna including two species of *Troposodon* Owen, and a new genus. Campbell (1973) based *Troposodon keuti*, the largest known species of the genus, on the holotype left ramus (SAM P14507) and a group of isolated teeth as paratypes, some of which pertain to other taxa (*Macropus* and *Protemnodon* Owen). There is another, smaller, species in the Kanunka Fauna close to *T. bowensis* Flannery and Archer in size and morphology. This is most completely represented by a fragment of a right ramus with broken dP₃ and complete M_{1,2} (UCMP 60747) that shows this species to be a small low-crowned form whose molars have posterior cinguli.

A new sthenurine genus is present, almost the size of *Sthenurus tindalei* Tedford with a short (equal to length of M₁) P₃ blade, lacking posterolabial crest, whose posterior end turns lingually like *Troposodon*. The high-crowned lower molars have rectilinear lophids like *Sthenurus* Owen, but they lack the premetacristid characteristic of *Troposodon*, the links are more sharply defined than in *Sthenurus* and the anterior lophid surfaces lack crenulations. There is a mandibular foramen characteristic of *Sthenurus* and *Procoptodon* Owen.

A right maxillary fragment (UCMP 56928) with M¹⁻² alveoli and a complete high-crowned M³ more clearly represents a large *Sthenurus*, about the size of *S. tindalei*.

Additional tooth and limb-bone fragments indicate that there are other sthenurines in the Kanunka fauna, but none can be clearly identified as either *Sthenurus* or *Procoptodon*.

Mammalia, Eutheria. Rodentia, Muridae: There are several isolated incisors, permineralized reddish-tan like the larger mammal material so there is no doubt about the presence of rodents in the Kanunka Fauna. Two specimens represent different taxa. A fragment of a right ramus with M_{1,2} (UCMP 60781) represents a small conulurine and a right M₁ pertains to a larger member of this group.

Toolapinna Fauna. This composite is assembled from local faunas collected from the vicinity of Toolapinna Waterhole, and from outcrops near Camel Swamp Yard and Keekalanna Soakage along the lower reach of the Warburton River. All of these sites occur in the upper fluvialite deposits of the Tirari Formation, the Pompapillina Member. As is typical of fluvialite environments, the fossil remains are very fragmentary and relatively rare in these deposits resulting in a lower diversity of taxa and uncertainties in taxonomic assignment. All the collections are part of the South Australian Museum holdings.

Lower Vertebrates. Unidentified fish, turtle, crocodile and bird remains were collected at these sites.

Mammalia, Marsupialia. Diprotodontidae: Remains of *Euryzygoma* sp. are the most abundant diprotodontid in the Toolapinna Fauna. This is a larger form than *E. duuense* (De Vis) (especially in the dimensions of the posterior molars) but not as large as the teeth in the Bluff Downs cranium (Archer and Wade 1976, plate 58). *Zygomaturus* is also represented by single specimen, a badly weathered skeleton that had been mired in Tirari red claystone near Keekalanna. The lower cheek teeth indicate a form larger and proportionately different from *Z. keani*, and closer to *Z. victoriae* (Owen) or *Z. trilobus* Mcleay. Fragments of teeth suggest other, smaller, diprotodontids in this fauna, but not *Diprotodon* Owen.

Palorchestidae: Fragments of associated lower molars (SAM P 250437) indicate the presence of *Palorchestes* cf. *azeal*.

Vombatidae (?): A broad upper incisor fragment, with flattened, enamel-covered anterior surface and broadly grooved posterior surface may represent a *Phascoglossus*-like large wombat.

Potoroidae: A right ramus with broken P₃ and

$M_{1,3}$ complete and the incisor base (SAM P 250500) appears to represent a new genus with short (about as long as length M_1), ungrooved premolar, *Bettongia*-like molars (lower crowned than in living species of that genus), and very long crowned lower incisor whose enamel reaches nearly to the open root beneath M_2 .

Macropodidae: Macropodinae: There are a number of fragmentary remains that represent small macropodines of uncertain generic reference. Large macropodines are best represented by metatarsals that indicate *Protemnodon* as large as *P. brehus*, and large *Macropus* (*Macropus*) cf. *titau* or *ferrugis* are present. A short fifth metatarsal (SAM P 250487), with laterally curved slender shaft (79 mm in length), lacks the strong plantar process of *Protemnodon* and resembles *Dendrolagus*. A similar short fourth metatarsal (SAM P 250486) could represent the same form.

Sthenurinae: An edentulous fragment of a left ramus (SAM P 25048) indicates a species of *Sthenurus* about the size of *S. tindalei* with mandibular features of that specific taxon. There is another sthenurine represented by a left maxillary fragment with dP^3 , M^{1-3} (SAM P 25504) that is similar in size to *Troposodon minor* (Owen), but differs in a number of significant ways: the presence of a forelink, well developed pre- and, particularly, post-paracristae, strong midlink, a premetacrista, distally tapering lophs, and a large, wide P^3 indicated by its crypt. In these features this apparently new taxon resembles *Procoptodon* and the new sthenurine.

DISCUSSION

Geological history. Widely scattered outcrops and limited subsurface information hinder reconstruction of the areal extent and regional sedimentology of the Tirari Formation. However, the consistent stratigraphy throughout the Tirari Desert does facilitate lithological correlation and subdivision of the unit into a basal channel filling member (Mampuwordu Member, only at Lake Palankarinna) developed in a higher gradient basin margin setting, passing upward and presumably laterally into red-brown gypsiferous mudstones characteristic of the main body of the Tirari Formation which in turn is truncated by a widespread fluvial unit (Pompapillina Member) that includes nested channel-fills and overbank red mudstone facies.

About two-thirds of Tirari deposition took place in an evaporitic environment of predominantly fine-grained clastic supply, the largest grains being reworked authigenic gypsum seed-crystals. The indications are that the depositional setting was a broad shallow basin in an arid climate with ephemeral saline lake(s) and marginal mud flats at, or just above, groundwater level.

A major change in sedimentary environment to widespread fluvial deposition is implied by the Pompapillina Member which represents a return to more mesic conditions and a higher watertable during deposition of the final third of the thickness of the Tirari Formation. In basin marginal settings, such as at Lake Kanunka, relatively deep dissection preceded deposition of the Pompapillina stream deposits. At all other sites this contact is also a disconformity, suggesting a hiatus of unknown magnitude that preceded the introduction of quartz sand-filled channels that blanketed all older rocks.

The depocenter for the Tirari Formation was evidently in the southern Simpson Desert as indicated by thickness increases in that direction and limited observations of directional sedimentary structures. The uplifts of Paleogene and Cretaceous rocks now followed by the Birdsville Track formed the eastern basin margin and provided centripetal drainage.

At the close of Tirari deposition the climate returned to at least seasonal aridity. The saline groundwater level remained high in the basin, eventually precipitating the gypcrete carapace that indurated the upper part of the Pompapillina Member.

Vertebrate history. Three faunas have been described from fluvial sands of the Tirari Formation. The oldest is the Palankarinna Fauna from the basal Mampuwordu Member at Lake Palankarinna, and the youngest are both from the Pompapillina Member, the Kanunka Fauna at Lake Kanunka, and the newly recognized Toolapinna Fauna from the Warburton River (Fig. 7). Remarkably, these faunas share few taxa, each has its own characteristic composition, and dominance of certain forms. The Palankarinna Fauna is particularly noteworthy in this regard, as it is represented by a large collection of relatively well preserved remains yet it is composed essentially of species of three mammalian genera, the diprotodontids *Zygomaturus* and *Meniscolophus* and the macropodid *Prionotenuus*. The taphonomic factors leading to such narrow samples of the biota

in a fluvial setting are perplexing, but could reflect an arid environment with limited resources. The Mampuwodu Member does contain aquatic vertebrates including teleost fish and lungfish indicating freshwater environments of deposition for these fluvial deposits, but distally these channels are very likely interbedded with red mudstones and they are succeeded vertically by gypsiferous red mudstones. Such facies relationships indicate an evaporative environment in which saline surface waters became widespread, suggesting climatic conditions that may have limited many Pliocene mammals. Bones of any kind, including those of aquatic vertebrates, are rare in the main body of the Tirari Formation.

The widespread fluvial environment of the Pompapillina Member contains abundant aquatic vertebrates and more diverse mammal faunas than the Mampuwodu Member. These facts imply a major interval of high water table and mesic environments followed the arid interval in which the main body of the Tirari Formation was deposited. The Kanunka Fauna shares *Zygomaturus* and *Priodontomys* with the Palankarina Fauna. The Toolapinna Fauna, less diverse taxonomically because it is a smaller

sample, is dominated by remains of the diprotodontid *Euryzygoma* with rare *Zygomaturus*.

These striking compositional differences make comparison among the younger Tirari faunas difficult, but they do not refute the lithological correlations that arrange them in relative temporal order. The occurrences and phylogenetic relationships of the diprotodontids provide stage-in-evolution correlations. The three diprotodontines have relative stratigraphic occurrences that agree with their cladistic relationships, namely *Meuscolophus* as the sister taxon of *Euryzygoma* and *Diprotodon*. The coeval occurrence of *Euryzygoma* and *Diprotodon* is also predicted by this phyletic relationship. The species of *Zygomaturus* also show change from *Z. keani* and the relatively primitive *Z. sp.* at Palankarina, to forms more like *Z. trilobus* or *Z. victoriae* in the youngest part of the Tirari.

Comparison with eastern Australian Pliocene faunas containing a diverse large marsupial component, such as Bluff Downs, Chinchilla and Bow, shows considerable similarity at the generic level. There are also some important alliances at the specific level, particularly when the central Australian material permits such identi-

Table 3. Occurrences of Pliocene vombatoid and macropodoid marsupials: "*" denotes the type locality of the species.

	Palankarina	Kanunka Toolapinna	Bluff Downs	Chinchilla	Bow
PALORCHESTIDAE					
<i>Palorchestes</i>	-	cf. <i>azeal</i>	-	<i>parvus</i>	<i>parvus</i>
DIPROTODONTIDAE					
<i>Euowenia</i>	-	-	cf. <i>grata</i>	<i>grata</i> *	?
<i>Meuscolophus</i>	<i>mawsoni</i> *	-	-	-	?
<i>Euryzygoma</i>	-	sp. large	cf. <i>dunense</i> , sp. large	<i>dunense</i> *	?
<i>Diprotodon</i>	-	sp.	-	cf. <i>optatum</i>	?
<i>Zygomaturus</i>	<i>keani</i> *	cf. <i>trilobus</i>	cf. <i>trilobus</i>	cf. <i>trilobus</i>	?
MACROPODIDAE					
<i>Lagorchestes</i>	-	n. sp., sp.	-	-	-
<i>Thylagale</i>	-	sp.	-	-	-
<i>Prionotomus</i>	<i>palankarinnicus</i> *	cf. <i>palankarinnicus</i>	-	<i>palankarinnicus</i>	-
<i>Kurrabi</i>	-	cf. <i>mahoneyi</i>	-	-	<i>mahoneyi</i> *, <i>merrivanensis</i> *, <i>chinchillaensis</i>
<i>Protemnodon</i>	?	<i>devisi</i> , sp.	<i>snewini</i>	<i>devisi</i> *, <i>chinchillaensis</i> *	-
<i>Macropus (M.)</i>	-	<i>pearsoni</i> , <i>woodsii</i>	-	<i>pan</i> *, <i>woodsii</i> *	-
<i>Macropus (O.)</i>	-	-	<i>pavana</i> *	-	<i>pavana</i>
<i>Macropus</i>	-	sp.	<i>naranda</i> *, cf. <i>dryas</i>	<i>dryas</i> *	<i>dryas</i>
<i>Dendrolagus</i>	-	cf.	-	?	cf.
<i>Troposodon</i>	-	<i>kenti</i> *, cf. <i>bowensis</i>	<i>bluffensis</i> *, <i>minor</i>	<i>minor</i> , <i>kenti</i>	<i>bowensis</i> *
<i>Sthenurus</i>	-	sp.	sp.	<i>notabilis</i> *	-
<i>Simosthenurus</i>	?	-	-	<i>antiquus</i> *	sp.

fication (Table 3). *Prionotemnus palankarimicus* has been identified at Chinchilla (*vide* Bartholomai, 1975), but the Chinchilla diprotodontines *Euryzygoma* and *Diprotodon* are more derived than *Meniscoplus*, and the *Zygomaturus* is larger than *Z. keani* and more like the Toolapinna form, suggesting that Palankarina is older than Chinchilla.

Diprotodon does occur at Chinchilla, as Woods (1962) and Stirton (in Stirton *et al.* 1968) believed. It is represented by a large mandible, the size of *D. optatum* (QM F 5580) collected at Chinchilla by K. Broadbent on 2 Feb. 1887 (data written on specimen). There is another mandible, QM F 10293, with Chinchilla preservation but without provenance data. Woods' (1960:396) geological study of the Chinchilla area found no evidence of fossils in the younger terraces incised into the Chinchilla Sand.

The combined diprotodontid fauna of Toolapinna and Kanunka strongly resembles that of Chinchilla. The Bluff Downs Fauna also contains *Zygomaturus* sp. and a large *Euryzygoma* sp. in addition to *Euowena* cf. *grata* ("Nototheriinae, genus indet." of Archer and Wade 1976), the latter shared with Chinchilla but not recognized in central Australia. The Bow diprotodontids have not yet been identified but apparently both diprotodontines and zygomaturines are present.

Comparison of the macropodids again reveals the greatest similarity with Chinchilla at the generic level (Table 3) and some specific similarities of the combined Toolapinna and Kanunka assemblages, particularly *Prionotemnus palankarimicus*, *Protomnodon devisi*, *Macropus (M.) woodsi*, and *Troposodon kenti*. There is less similarity with the Bluff Downs and Bow Faunas which may be older assemblages than Chinchilla as concluded by Archer and Wade (1976).

Geochronology. Having established the relative age relationships and correlations of the Tirari faunas with assemblages in eastern Australia, we are in a position to calibrate this succession using geochronological information derived from isotope dating and magnetostratigraphy.

The age of the Bluff Downs Fauna is constrained by radioisotopic ages on the overlying Allensleigh basalt. Whole rock dates range from 4.1-4.6 Ma based on samples from different parts of the outcrop but these may not be significantly different from one another. Archer and Wade (1976) believed the minimum age for the basalt

was 4.00 ± 0.12 Ma based on standard error estimates. The occurrence of murid rodent remains at Bluff Downs and not at Hamilton where the fauna lies beneath basalt flows of 4.47 Ma suggest that 4.0 Ma maybe a minimum estimate for the Bluff Downs Fauna as well as the first occurrence of rodents in Australia.

Additional data bearing on the calibration of the Kanunka and Chinchilla faunas can be determined from the paleomagnetic signature of the Tirari Formation. As discussed above, the Tirari Formation falls within a predominantly reversely magnetized interval that is paleontologically constrained to represent the later part of the early Pliocene Gilbert Chron. Placement within the Gilbert (Fig. 7) is limited by the occurrence of rodents in the Pompapillina Member which constrain the maximum age for the long reversed interval in the upper part of the Tirari Formation to be 3.9 Ma and a minimum age to be 3.4 Ma at the end of the Gilbert (Fig. 7). The age of the base of the Tirari Formation is more problematic depending on the span of the hiatus beneath the Pompapillina Member. If this is short at the 10^5 yr scale then the normal events at the base of the Tirari Formation in the Warburton outcrops probably represent the normally polarized subchrons in mid-Gilbert, but if 10^6 yr or greater, Chron 5 or older normal intervals might be indicated. In this synthesis we have chosen the former alternative and thus correlate the long reversed interval containing the Pompapillina Member to the late part of the Gilbert Chron. The Mampuwordu Member, one site at the top of which is apparently reversed, would lie near the beginning of this interval, the Pompapillina toward the end. This calibration does no violence to the paleontological relationships and, although the data does not constrain it as much as we would prefer, we accept it as a working hypothesis.

In conclusion, the geochronological age of the Tirari Formation outcrops seems most parsimoniously attributed to the late Gilbert Chron when all the evidence both paleontological and physical is considered. In this hypothesis the Mampuwordu Member with its Palankarina Fauna would be approximately 3.9 Ma, the Pompapillina Member with the Kanunka and Toolapinna faunas would be approximately 3.4 Ma. At a minimum these faunal levels are separated by about 0.5 Ma, probably sufficient time to account for the biological changes implied in the comparisons made among them.

ACKNOWLEDGEMENTS

This work was supported by a grant from the Australian Research Grants Committee in 1981 and the National Geographic Society (2179-80, 2579-82 and 2652-83). We are indebted to our field companions of the 1980 expedition; Drs John Bye and David Catcheside, Flinders University, Mr Paul Lawson, Adelaide and the late Dr Dominic Williams and to the members of the 1983 expedition; Mr Ed Bailey and Ms Sandi Tartowski, Flinders University, and Mr Paul Lawson, Adelaide. The success of our field work is due in part to their hard work, dedication and companionship. Aerial reconnaissance in 1980 was provided by Dr Roly Byron-Scott, Flinders University and in 1983 by Mr Peter Dunn of New Kalamurina Station. The Dunn family offered traditional bush hospitality and aided us in many ways as did Brian and Cath Oldfield while at Etadunna Station and Kevin Oldfield of Clayton Station.

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Accepted 25 May, 1992